The Kuo Convective Parameterization Scheme As Implemented in RAMS

Christopher L. Castro
Mesoscale Modeling

The Kuo convection scheme was originally developed in H.L. Kuo (1974). RAMS uses a modified version of the Kuo scheme summarized by Molinari (1985).

Advantages:

- The scheme is relatively simple and is based on the physical principle that convection consumes the convective available potential energy (CAPE).
- Though there are tunable threshold values that can be user-defined, only the moisture partitioning parameter (b) is purely empirical (ironically, taken from Fritch and Chappell who parameterize the entire convective process empirically!)

Disadvantage:

- Convection is modeled as a one dimensional process in the vertical only, which neglects the complex dynamics of convection within a three-dimensional cloud. Probably the greatest source of error in the scheme (e.g. Nicholls and Pielke, ???)

NOTE: In this discussion, a detailed description of the some of the ancillary subroutines relating to computation of thermodynamic characteristics of the sounding will be omitted.

SUMMARY OF KUO PARAMETERIZATION EQUATIONS THAT FEEDBACK TO RAMS LEVEL 1

A convective heating term:

$$\left(\frac{\partial\theta}{\partial t}\right)_{CON} = L(1-b)\pi^{-1}I\frac{Q_h}{\int_{z_0}^{z_{CT}} Q_h dz}$$

A water vapor (q_V) tendency term:

$$\left(\frac{\partial q_V}{\partial t}\right)_{CON} = bI\frac{Q_m}{\int_{z_G}^{z_{CT}} Q_m dz}$$

A convective precipitation (q_L) rate:

$$\left(\frac{\partial q_L}{\partial t}\right)_{CON} = (1-b)Ir$$

Symbol	**Meaning**
I	Rate at which resolvable scale supplying moisture to a particular grid column
b	Moisture partitioning parameter, which determines fraction of I used to increase moisture of column
1-b	Fraction of moisture precipitated out (precipitation efficiency)
Q_m, Q_h	Vertical profiles of convective heating and moistening
π	Exner function
r	Precipitation reduction factor

KUO SUBROUTINE A
ENVIRON

Determines if there is sufficient CAPE to initiate convection by Kuo scheme

Dependent Variables required from level one (6)

T_{ENV}, θ_{ENV}, q_v, u(k), v(k), w(k)

Independent Variables (1)

z(k)

Constants defined in routine(5)

$$c_p = 1004$$
$$g = 9.80$$
$$L_v = 2.5 \times 10^6$$
$$R = 287$$
$$P_o = 10{,}000$$

Steps

1. Compute a moist static energy profile at each model level k.

$$h_m = c_p T_{ENV} + gz + Lq \qquad (1a)$$

2. Check for conditional instability and any upward motion greater than a specified minimum velocity (e.g > 1 cm s^{-1}) under 3000 m.

- If $dh_m/dz < 0$ at any point
  → Continue, conditionally unstable at least through one layer

- If $dh_m/dz > 0$ through the entire sounding
  → Stable atmosphere **STOP**

3. Interpolate model vertical profile to higher resolution (60 levels). Calls interpolation function for u, v, w, θ_{ENV}, and q. Higher resolution (200 m) below 3000 m and coarser resolution (500 m) above.

4. Compute Exner function at each model level k using the hydrostatic relation:

$$d\pi = -g\frac{dz}{\theta_{ENV}} \quad (2a)$$

Then determine:

$$T_{ENV}^{*} = \frac{\theta_{ENV}\pi}{c_p} \quad (3a)$$

$$P = P_o\left(\frac{\pi}{c_p}\right)^{\frac{c_p}{R}} \quad (4a)$$

$$\rho = \frac{P}{\left(RT_{ENV}^{*}\left(1+0.61q_v\right)\right)} \quad (5a)$$

5. Function to compute $\theta_{e(ENV)}$ from π, q_v, and T_{ENV}^{*}

6. Determine if there is a maximum value of θ_{ENV} or $\theta_{e(ENV)}$ below 3 km. This is the source level (src) for air lifted from near the surface (θ_{src})

7. Using T_{src}, P_{src}, q_{src} a function computes the thermodynamic properties of the LCL (T_{LCL}, P_{LCL}, z_{LCL}).

8. If the upward motion at LCL is less than the threshold upward velocity,

STOP.

9. Define new potential temperature of the source level of the air uplifted from the source region to the LCL.

$$\theta_{up} = \theta_{src}\, exp\left(\frac{Lq_{src}}{c_p T_{LCL}}\right) \qquad (6a)$$

10. Using θ_{up} Call function that computes rise along a moist adiabat (θ_m) from the LCL to the top of the model.

11. If the sign of the CAPE is positive, Kuo scheme initiated

$$g \int_{z_{LCL}}^{z_{top}} \frac{(\theta_m - \theta)}{\theta} dz > 0$$

Additional dependent variables computed in this subroutine (6)

$h_m, \pi, T^*_{ENV}, P, \rho, \theta_{up}$

Additional dependent variables computed in ancillary subroutines (4)

$T_{LCL}, P_{LCL}, z_{LCL}, \theta_m$

KUO SUBROUTINE B
KUOCP

Dependent Variables required from level one or Subroutine A (11)

ρ_{LCL}, $q_v(k)$, $q_{vs}(k)$, w_{LCL}, L, c_p, θ_{src}, T_{LCL}, $\theta_{ENV}(k)$, u(k), v(k)

Independent Variables (~~1~~) 2

z(k), t

Steps

1. Compute the vertical moisture flux into the cloud layer. This is defined as the moisture supply (I)

$$I = \rho_{LCL} q_{LCL} w_{LCL} \tag{1b}$$

2. Compute θ of the updraft at the LCL, using source region determined in Subroutine A.

$$\theta_{up(LCL)} = \theta_{src} \exp\left(\frac{Lq_{src}}{c_p T_{LCL}}\right) \tag{2b}$$

3. Compute θ_{up} from LCL to model top assuming moist adiabatic rise (call function).

Determine if the level at which $\theta_{up} > \theta_{ENV}$. This defines the point where the parcel is positively buoyant or the level of free convection (LFC). If no LFC is reached, convection is beyond the model top and **STOP**.

Determine equilibrium level as point where $\theta_{up} < \theta_{ENV}$. Cloud top (CT) is arbitrarily defined as the next model level up.

4. Check to see if area of positive buoyancy at least 3000 m deep or cloud top > 500 mb (e.g. deep convection only). If not, **STOP**.

5. Compute the areas of positive CAPE and convective inhibition (CIN) at the top and bottom of soundings.

$$CIN_{low} = \sum_{z=sfc}^{z=LCL} \left(\theta_{up} - \theta_{ENV}\right)\Delta z \qquad (3b)$$

$$CAPE = \sum_{z=LCL}^{z=CT} \left(\theta_{up} - \theta_{ENV}\right)\Delta z \qquad (4b)$$

$$CIN_{high} = \sum_{z=CT}^{z=EL} \left(\theta_{up} - \theta_{ENV}\right)\Delta z \qquad (5b)$$

In order for convection to be activated, require that:

$$CAPE > 1.5\left(CIN_{low}\right) \qquad CAPE > 1.05\left(CIN_{low} + CIN_{high}\right)$$

If not, **STOP**.

6. Downdraft model

Find θ_e minimum (level of free sink) above the could top. If no θ_e, set LFS to model top. θ_e already computed in Subroutine A.

Compute the maximum difference (D) between the θ_{up} and θ_{ENV}.

$$D = MAX\left(\theta_{up} - \theta_{ENV}\right) \qquad (6b)$$

If this difference > 2.5°, set D to 5.

Define a downdraft temperature at the LCL and the surface, such that:

$$\theta_{down(LCL)} = \theta_{ENV(LCL)} - 0.2D \tag{7.1b}$$

$$\theta_{down(SFC)} = \theta_{ENV(SFC)} - D \tag{7.2b}$$

In the cloud, θ_{down} is assumed a linear function from the LCL to LFS. For each z model level

$$\theta_{down} = \theta_{down(LCL)} + \frac{\theta_{down(LFS)} - \theta_{down(LCL)}}{z_{LFS} - z_{LCL}}\left(z - z_{LCL}\right) \tag{7.4b}$$

Then from surface to LCL, assume a (different) linear function:

$$\theta_{down} = \theta_{down(SFC)} + \frac{\theta_{down(LCL)} - \theta_{down(SFC)}}{z_{LCL} - z_{SFC}}\left(z - z_{SFC}\right) \tag{7.5b}$$

7. Weighted average of downdraft relative to updraft

Assume downdraft weighting factor (Λ) is zero at LFS, half of updraft at cloud base, and equal to updraft at the ground. Predefine Λ at four levels:

$$\begin{aligned} \Lambda_{LFS} &= 0 \\ \Lambda_{LCL} &= 0.1 \\ \Lambda_{DIV} &= 0.2 \\ \Lambda_{SFC} &= 1 \end{aligned} \tag{8.1b}$$

"DIV" is the model level closest to 800 m.

Weighting functions assumed to behave linearly in between the levels at which they are predefined. For example, from LCL to LFS:

$$\Lambda = \Lambda_{LCL} + \frac{\Lambda_{LFS} - \Lambda_{LCL}}{z_{LFS} - z_{LCL}}\left(z - z_{LCL}\right) \tag{8.2b}$$

8. Fritch-Chappell precipitation efficiency parameter (b)

Environmental shear (S) defined through the cloud layer from the LFC to CT:

$$S = \frac{\sqrt{(u_{CT} - u_{LFC})^2 + (v_{CT} - v_{LFC})^2}}{z_{CT} - z_{LFC}} \tag{9b}$$

Precipitation efficiency (1-b) defined as, if $S > 1.35$

$$1 - b = 1.591 - 0.639S + 0.0953S^2 - 0.00496S^3 \tag{10.1b}$$

If $S < 1.35$

$$1 - b = 0.9 \tag{10.2b}$$

9. Vertical profile of convective heating/moistening

Use a weighted average of updraft and downdraft potential temperatures to determine a new potential temperature affected by the convective process (θ_{CON}) at each level z:

$$\theta_{CON} = \Lambda\theta_{down} + (1 - \Lambda)\theta_{up} \tag{11b}$$

Heating profile (Q_h) at each level z is then:

$$Q_h = \theta_{CON} - \theta_{ENV} \tag{12b}$$

Moisture profile (Q_m) difference between vapors of updraft and environment in the cloud layer. Below cloud base, air is dried by I. Downdrafts are assumed to have to effect.

From LCL to CT

$$Q_m = q_{vs} - q_v \tag{13.1b}$$

Below LCL

$$Q_{dry} = q_v \tag{13.2b}$$

10. Integrate profiles and compute convective heating and water vapor tendency terms at each level z.

$$\left(\frac{\partial\theta}{\partial t}\right)_{CON} = L(1-b)\pi^{-1}I\frac{Q_h}{\int_{z_G}^{z_{CT}} Q_h dz} \tag{14b}$$

$$\left(\frac{\partial q_V}{\partial t}\right)_{CON} = bI\frac{Q_m}{\int_{z_G}^{z_{CT}} Q_m dz} \tag{15b}$$

11. Final checks

Convective heating? If…

$$\int_{z_G}^{z_{CT}} Q_h dz < 0$$

STOP

Minimum average temperature difference. If…

$$\theta_{CON} - \theta_{ENV} < 0.1$$

STOP

13. Precipitation rate

Precipitation reduction factor (r)

$$r = \frac{\theta_{CON}}{\theta_{ENV} + Q_h dt} \le 1 \qquad r \le 1 \tag{16b}$$

Precipitation rate:

$$\left(\frac{\partial q_L}{\partial t}\right)_{CON} = (1 - b)Ir \qquad (17b)$$

Additional dependent variables computed in this subroutine (17)

I, $\theta_{up(LCL)}$, CIN_{low}, CAPE, CIN_{high}, D, $\theta_{down}(k)$, $\Lambda(k)$, S, b, $\theta_{CON}(k)$, $Q_h(k)$, $Q_m(k)$, r and three heating + water vapor tendency terms.

Additional dependent variables computed in ancillary subroutines (1)

$\theta_{up}(k)$